

NEW, CONTINUATION, DIVISIONAL OR  
CONTINUATION-IN-PART APPLICATION  
UNDER 37 C.F.R. §1.53(b)

Attorney Docket No. 6550-000022

Express Mail Label No. EJ 948 538 663 US

Date October 11, 1999

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Hon. Commissioner of Patents and Trademarks  
Washington, D. C. 20231

Sir:

Transmitted herewith for filing under 37 C.F.R §1.53(b) is a patent application for

**CONDUCTIVE ISOSTRUCTURAL COMPOUNDS**

identified by: ☒ Inventor(s): Mercouri G. Kanatzidis, Duck Young Chung, Stephane  
DeNardi and Sandrine Sportouch  
or ☒ Attorney Docket No. (see above)

**1. Type of Application**

☒ This application is a new (non-continuing) application.

☐ This application is a ☐ continuation / ☐ divisional / ☐ continuation-in-part of prior application No. \_\_\_\_\_. Amend the specification by inserting before the first line the sentence:

--This is a [continuation/division/continuation-in-part] of United States patent application No. \_\_\_\_\_, filed \_\_\_\_\_.--

☐ The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied, is considered part of the disclosure of the accompanying application and is hereby incorporated by reference therein.

If for some reason applicant has not requested a sufficient extension of time in the parent application, and/or has not paid a sufficient fee for any necessary response in the parent application and/or for the extension of time necessary to prevent the abandonment of the parent application prior to the filing of this application, please consider this as a Request for an Extension for the required time period and/or authorization to charge our Deposit Account No. 08-0750 for any fee that may be due. THIS FORM IS BEING FILED IN TRIPLICATE: one copy for this application; one copy for use in connection with the Deposit Account (if applicable); and one copy for the above-mentioned parent application (if any extension of time is necessary).

**2. Contents of Application**

a. Specification of 17 pages;

- ☐ A microfiche computer program (Appendix);  
☐ A nucleotide and/or amino acid sequence submission;

☐ Because the enclosed application is in a non-English language, a verified English translation ☐ is enclosed ☐ will be filed.

☐ Cancel original claims \_\_\_\_\_ of the prior application before calculating the filing fee. (At least one original independent claim must be retained for filing date purposes.)

b. ☒ Drawings on eight (8) sheets showing Figures 1-5;

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- c. ☒ A signed Oath/Declaration ☐ is enclosed / ☒ will be filed in accordance with 37 C.F.R. §1.53(f).

The enclosed Oath/Declaration is ☐ newly executed / ☐ a copy from a prior application under 37 C.F.R. §1.63(d) / ☐ accompanied by a statement requesting the deletion of person(s) not inventors in the continuing application.

d. **Fees**

FILING FEE	Number				Number				Basic Fee
CALCULATION	Filed				Extra		Rate	\$760.00	
Total Claims	31	-	20	=	11	x	\$18.00	=	\$198.00
Independent Claims	4	-	3	=	1	x	\$78.00	=	\$78.00
Multiple Dependent Claim(s) Used							\$260.00	=	
FILING FEE - NON-SMALL ENTITY								\$1,036.00	
FILING FEE - SMALL ENTITY: Reduction by 1/2									
[ ] Verified Statement under 37 C.F.R. §1.27 is enclosed.									
[ ] Verified Statement filed in prior application.									
Assignment Recordal Fee (\$40.00)									
37 C.F.R. §1.17(k) Fee (non-English application)									
TOTAL									

- ☐ A check is enclosed to cover the calculated fees. The Commissioner is hereby authorized to charge any additional fees that may be required, or credit any overpayment, to Deposit Account No. 08-0750. A duplicate copy of this document is enclosed.

- ☒ The calculated fees will be paid within the time allotted for completion of the filing requirements.

- ☐ The calculated fees are to be charged to Deposit Account No. 08-0750. The Commissioner is hereby authorized to charge any additional fees that may be required, or credit any overpayment, to said Deposit Account. A duplicate copy of this document is enclosed.

3. **Priority Information**

- ☐ **Foreign Priority:** Priority based on \_\_\_\_\_ Application No. \_\_\_\_\_, filed \_\_\_\_\_, is claimed.

- ☐ A copy of the above referenced priority document ☐ is enclosed / ☐ will be filed in due course, pursuant to 35 U.S.C. §119(a)-(d).

- ☒ **Provisional Application Priority:** Priority based on United States Provisional Application No. 60/103,961, filed October 13, 1998, is claimed under 35 U.S.C. §119(e).

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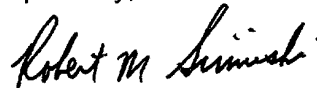
**4. Other Submissions**

- ☐ A Preliminary Amendment is enclosed.
- ☐ An Information Disclosure Statement, \_\_\_\_\_ sheets of PTO Form 1449, and \_\_\_\_\_ patent(s)/publications/documents are enclosed.
- ☐ A power of attorney
- ☐ is submitted ☐ with the new Oath/Declaration.
- ☐ is of record in the prior application and ☐ is in the original papers / ☐ a copy is enclosed.
- ☐ An Assignment of the invention
- ☐ is enclosed with a cover sheet pursuant to 37 C.F.R. §§3.11, 3.28 and 3.31.
- ☐ is of record in a prior application. The assignment is to \_\_\_\_\_, and is recorded at Reel \_\_\_\_\_, Frame(s) \_\_\_\_\_.
- ☐ An Establishment of Assignee's Right To Prosecute Application Under 37 C.F.R. §3.73(b), and Power Of Attorney is enclosed.
- ☒ An Express Mailing Certificate is enclosed.
- ☐ Other: \_\_\_\_\_

Attention is directed to the fact that the correspondence address for this application is:

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Respectfully,



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Sir:



**EXPRESS MAILING CERTIFICATE**

Applicant: Mercouri G. Kanatzidis, Duck Young Chung, Stephane DeNardi and  
Sandrine Sportouch

Serial No (if any):

For: CONDUCTIVE ISOSTRUCTURAL COMPOUNDS

Docket: 6550-000022

Attorney: Robert M. Siminski

"Express Mail" Mailing Label Number ..... EJ 948 538 663 US

Date of Deposit ..... October 11, 1999

I hereby certify and verify that the accompanying **return postcard, transmittal letter, 17-page patent application including at least one claim and an abstract and eight (8) sheets of drawings showing Figures 1-5** are being deposited with the United States Postal Service "Express Mail Post Office To Addressee" service under 37 C.F.R. 1.10 on the date indicated above and (is) are addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

Signature of Person Mailing Document(s)  
Carrie Hood

## CONDUCTIVE ISOSTRUCTURAL COMPOUNDS

### SPONSORSHIP

Work on this invention was sponsored in part by the Office of Naval Research, Grants N00014-94-1-0935 and N00014-98-1-0443 and Defense Advanced Research Projects Agency Grant DAAG55-97-1-0184. The Government may have certain rights to the invention.

### FIELD OF THE INVENTION

This invention relates generally to new compounds exhibiting crystal lattice morphologies and, more particularly, to conductive compounds having NaCl-type cubic crystal lattice structures.

### BACKGROUND OF THE INVENTION

Semiconductor materials are at the core of current technological infrastructure and continuing advancements. Various semiconductors enable many technologies. For example, Si and Ge enable high speed computing, GaAs, InSb and their derivatives enable optoelectronics and communication devices, Si and GaAs are the vital components of solar energy converters, GaN and GaAs alloys enable solid state lasers,  $\text{Bi}_2\text{Te}_3$  alloys enable thermoelectric cooling, and PbS, PbSe and HgCdTe are used in medium and long wavelength radiation detection.

Semiconductor materials used in solid state lasers, photovoltaic cells, optoelectronic devices and radiation detection, for example, must not only be excellent electronic conductors, but also have the appropriate energy band configuration or "band gap" for those applications. As more than one material is used in layers, the difference in the band gap between the various semiconductor materials used is also critical. For example, photovoltaic cells can use two semiconductor materials to produce a rectifying heterojunction. The advantages of utilizing this design include the ability to choose materials with properties appropriate for each component of the device and the reduced necessity for compromise with the property requirements of other components of the device. An example of this is the use of a wide band gap "window" semiconductor material as a barrier layer on a more narrow band gap "absorber" semiconductor material. The amount of radiation absorbed and therefore the electrical current generated in the device, increases with the decreasing band gap width, while the diffusion potential obtainable within the device, and therefore the electrical voltage generated in the device, increases with band gap width. Thus, the absorber material is chosen to maximize the solar radiation absorbed and affords a reasonable diffusion potential, while window material is chosen to absorb a minimum amount

of solar radiation. Therefore, the closer the actual band gap to the desired, theoretical band gap of the semiconductor materials, the more efficient the photovoltaic cell. Many current semiconductor materials are limited in that they do not allow for fine adjustment of the band gap. Furthermore, some semiconductor materials contain volatile elements causing changes in the composition of the materials and consequently unwanted changes in the band gap.

In thermoelectric devices, it is also critical to have semiconductor materials that have specific properties. Such devices may be used for heating, cooling, temperature stabilization, power generation and temperature sensing. Modern thermoelectric coolers typically include an array of thermocouples.

Thermoelectric devices are essentially heat pumps and power generators which follow the laws of thermodynamics in the same manner as mechanical heat pumps, refrigerators, or any other apparatus used to transfer heat energy. The efficiency of a thermoelectric device is generally limited to its associated Carnot cycle efficiency reduced by a factor which is dependent upon the thermoelectric figure of merit ( $zT$ ) of the materials used in fabrication of the thermoelectric device. The figure of merit represents the coupling between electrical and thermal effects in a material. The basic thermoelectric effects are the Seebeck and Peltier effects. The Seebeck effect is the phenomenon underlying the conversion of heat energy into electrical power and is used in thermoelectric power generation. The complementary effect, the Peltier effect, is the phenomenon used in thermoelectric refrigeration and is related to heat absorption accompanying the passage of current through the junction of two dissimilar materials.

While thermoelectric materials such as alloys of  $\text{Bi}_2\text{Te}_3$ ,  $\text{PbTe}$  and  $\text{BiSb}$  were developed thirty to forty years ago, the efficiency of such thermoelectric devices remains relatively low at approximately five to eight percent energy conversion efficiency.

Therefore it would be desirable to have semiconductor materials that are not only good conductors but have a range of band gaps to fit a wide number of applications. It would be further desirable to have materials in which the band gaps could be adjusted to give the desired band gap for the appropriate application. These materials should also be thermal and chemically stable.

Furthermore, it would be desirable to have thermoelectric materials that have a high thermoelectric figure of merit. Use of such materials would produce thermoelectric devices with high efficiencies.

## SUMMARY OF THE INVENTION

The present invention relates to new isostructural compounds having the general formula  $A_nM_mM'_nQ_{2n+m}$  where A is a metal selected from the group consisting essentially of the alkali metals, lithium (Li), sodium (Na), potassium (K), rubidium (Rb), or cesium (Cs) or the transition metals silver (Ag) or thallium (Tl) and mixtures thereof, M is selected from lead (Pb), tin (Sn), germanium (Ge), calcium (Ca), strontium (Sr), barium (Ba), any divalent transition metal and mixtures thereof, M' is selected from bismuth (Bi), antimony (Sb) and mixtures thereof, and Q is selected from the group consisting essentially of sulfur (S), selenium (Se), or tellurium (Te) and mixtures thereof. These compounds possess an NaCl-type cubic lattice crystal structure where A, M and M' occupy the Na sites and Q occupies the Cl (chlorine) sites. This family of compounds combine isotropic morphology, an advantageous property for device processing, with low thermal conductivity and widely ranged electrical conductivity. Further, certain properties such as the electrical properties of the compounds can be controlled by varying the values for n and m. The isostructural compounds of the present invention are therefore good candidates for semiconductor applications in thermoelectronic devices, detectors, and photovoltaic cells, by way of non-limiting example.

Additional objects, advantages, and features of the present invention will become apparent from the following description and appended claims, taken in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is an illustration of the crystal structure of  $A_nPb_mB'_nQ_{2n+m}$ ;

Figure 2A is a graph showing the infrared absorption spectrum of  $K_2PbBi_2Se_5$ ;

Figure 2B is a graph showing the infrared absorption spectrum of  $KPb_4BiSe_6$ ;

Figure 2C is a graph showing the infrared absorption spectrum of  $KPb_8BiSe_{10}$ ;

Figure 2D is a graph showing the infrared absorption spectrum of PbSe;

Figure 3 is an illustration showing a multispectral sensor with a two-materials stacked structure;

Figure 4 is a graph showing the effect of increasing temperature on the resistivity of  $KPb_8BiTe_{10}$ ; and

Figure 5 is a graph showing the effect of increasing temperature on the Seebeck coefficient of  $KPb_8BiTe_{10}$ .

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides new isostructural compounds having the general formula  $A_nM_mM'_nQ_{2n+m}$  where A is selected from a group of cations selected from the group consisting essentially of lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs),

silver (Ag) or thallium (Tl) and mixtures thereof, M is selected from lead (Pb), tin (Sn), germanium (Ge), calcium (Ca), strontium (Sr), barium (Ba), any divalent transition metal and mixtures thereof, M' is selected from bismuth (Bi), antimony (Sb) and mixtures thereof, and Q is selected from the group consisting essentially of sulfur (S), selenium (Se), or tellurium (Te) and mixtures thereof.

The variables n and m can be any number greater than zero. Preferably, n and m are integers. While the variables n and m can theoretically be any integer, preferably, n and m are between 1 and 20. Additionally, the ratio of cations to anions present in the compounds of the present invention will preferably be 1:1.

The compounds of the present invention can be synthesized utilizing at least two different groups of starting materials or from the pure elements themselves. According to one embodiment, the group of starting materials are  $A_2Q$ , M, M' and Q and under another embodiment the group of starting materials are  $A_2Q$ ,  $M'_2Q_3$ , M and Q, wherein M and Q can be in the form of MQ as will be described below. In yet another embodiment, the pure elements, A, M, M' and Q, in the correct stoichiometric ratios can be used to synthesize the compounds of the present invention.

$A_2Q$  can be prepared by reacting stoichiometric amounts of the elemental A (2 moles) with the elemental Q (1 mole) in liquid ammonia. When the reaction is complete, the ammonia is removed by evaporation at ambient temperature. The resulting product is dried and ground to give a fine homogeneous powder.

$M'_2Q_3$  can be generally prepared by reacting stoichiometric amounts of elemental Bi or Sb (2 moles) and elemental Q (3 moles) at 800 °C for about 1-3 days at ambient pressure or optionally under a vacuum to reduce reaction times. Alternatively, bismuth telluride (Johnson Matthey/AESAR Group, Seabrook, NH) and bismuth selenide (Cerac, Inc, Milwaukee, WI) can be obtained commercially.

MQ can be synthesized, for example, by thoroughly mixing stoichiometric amounts (1 mole each) of elemental Pb, Sn, Ge, Ca, Sr, Ba, or any divalent transition metal and Q and loading the mixture into a quartz tube at a residual pressure of less than  $10^{-4}$  Torr. The mixture is then heated to 800 °C over a 24 hour period and the temperature maintained for an additional 24 hours. The mixture is then cooled by quenching in water and the resulting ingot is crushed to a fine powder. The powder is then reloaded into a quartz tube and heated to 800 °C over a 24 hour period. The temperature of the mixture is maintained at 800 °C for an additional 24 hours and then slowly cooled to 300 °C at a rate of about 4 °C/hr and subsequently to 50 °C over about 6 hours. The resulting ingots are ground to a fine powder prior to synthesis of the compounds of the present invention.



Upon forming each of the compounds included in the groups of starting materials, the isostructural compounds of the present invention are synthesized by thoroughly mixing and loading the chosen starting materials into a carbon coated quartz or capped graphite tube at a residual pressure less than  $10^{-4}$  Torr, i.e., either the group of  $A_2Q$ , M metal, M' metal and elemental Q or the group  $A_2Q$ ,  $M'_2Q_3$  and MQ. The mixture is heated to 700 °C at a rate of about 30 °C/hr. After maintaining the temperature at 700 °C for approximately 3 days, the mixture is cooled to 300 °C at a rate of 5 °C/hr followed by cooling to 50 °C in about 12 hours. The resulting product is washed with degassed dimethylformamide and water in a nitrogen atmosphere. After further washing with diethyl ether and subsequent drying, the isostructural compounds of the present invention are obtained as shiny black chunks exhibiting the above described cubic phase.

The compounds of the present invention can also be synthesized from the pure elements. The appropriate elements for the desired compound, A, M, M' and Q, are mixed together in the correct stoichiometric ratios and sealed in a quartz tube under vacuum, i.e.,  $< 10^{-3}$  Torr. The mixture is then heated in a direct flame until molten. Subsequent cooling of the melt yields the corresponding compound. To synthesize  $KSnBiSe_3$ , by way of non-limiting example, 0.01 mole (0.39g) of potassium, 0.01 mole (1.18 g) tin, 0.01 mole (2.09g) bismuth and 0.03 mole (2.37g) of selenium were mixed, placed in a quartz tube and sealed under vacuum at  $< 10^{-3}$  Torr. The mixture was heated in a direct flame until molten and subsequently cooled to yield the desired product,  $KSnBiSe_3$ .

As noted above, the isostructural compounds of the present invention have a cubic crystal lattice structure of the same type as NaCl, wherein the cations (or metals) occupy the Na sites and the anions occupy the Cl sites. The cations, although differing in charge, are similar in size and tend to become randomly dispersed throughout the structure as shown in Figure 1. This cubic crystal structure is independent of the values for n and m and depends only on the elements selected to form the isostructural compounds. A property of this cubic structure of the compounds of the present invention is a morphology of low anisotropy which is desirable for fabricating electronic and optical devices, by way of non-limiting example. The cubic structure also gives rise to relatively high carrier mobilities and ease of crystal growth and processing. The compounds of the present invention also have relatively high melting point temperatures which are considered to be indicative of a high degree of structural stability. The melting temperatures of a significant number of the sample compounds of the present invention are greater than 850°C (Table 1).

The isostructural compounds of the present invention include band gaps which are tunable. By "band gaps" it is meant that there is an energy difference between the highest occupied electron state and the lowest unoccupied electron state in the isostructural

compounds. Further, by "tunable" it is meant that this energy difference can be manipulated to obtain the desired band gap. One way of tuning the band gaps of the isostructural compounds is by varying the values of n and m (Table 1). For example, the band gap of  $\text{KPbBiSe}_3$  ( $n=1$ ,  $m=1$ ) was measured at  $\sim 0.60$  eV which is in the desirable range for IR radiation detection. The compounds  $\text{K}_2\text{PbBi}_2\text{S}_5$  ( $n=2$ ,  $m=1$ ) and  $\text{KPb}_2\text{BiS}_4$  ( $n=1$ ,  $m=2$ ) have optical band gaps of 1.1 and 0.76 eV respectively. Depending on the values for n and m in  $\text{A}_n\text{M}_m\text{M}'_n\text{Q}_{2n+m}$ , a relatively wide range of band-gaps is possible, i.e., from about 0.05 eV to 1.55 eV. Band gap values for other representative isostructural compounds are given in Table 1. Infrared spectra showing the band-gap transition are shown in Figures 2A-C. For comparison purposes, the infrared spectrum for PbSe, which is commonly used as an IR detector and has an NaCl-type cubic crystal lattice structure, is shown in Figure 2D.

Another way of tuning the band gaps of the isostructural compounds of the present invention is by selecting certain cations and anions for A and Q, respectively. For example, if Se is chosen for Q and K is chosen for A, the isostructural compound  $\text{KPb}_2\text{BiSe}_4$  has a band gap of 0.66 eV. If Q is changed from Se to Te, the corresponding compound  $\text{KPb}_2\text{BiTe}_4$  has a band gap of less than 0.4 eV (Table 1). Depending on the application, appropriate band gaps can be chosen which would correspond to certain members of each family. One member of the family may be more appropriate for long wavelength detection, while another may be appropriate for short wavelength detection such as is used by IR lasers.

Yet another way of controlling the band gaps for the overall composition is by combining various individual isostructural compounds of the present invention to form solid solutions of the type  $(\text{Li,Na,K,Rb,Cs,Ag,Tl})_n(\text{Sn, Pb, Ge, Ca, Sr, Ba})_m(\text{Bi,Sb})_n(\text{S,Se,Te})_{2n+m}$ . By "solid solutions" what is meant is a single, solid, homogenous crystalline phase containing two or more chemical species. A so-called solid solution would be made up of at least two distinct chemical species such as  $\text{A}_n\text{Pb}_m\text{Bi}_n\text{Se}_{2n+m}$  and  $\text{A}_n\text{Pb}_m\text{Bi}_n\text{Te}_{2n+m}$  where Q represents two different anions (Se and Te), or  $\text{K}_n\text{Pb}_m\text{Bi}_n\text{Q}_{2n+m}$  and  $\text{Ag}_n\text{Pb}_m\text{Bi}_n\text{Q}_{2n+m}$  where A now represents two different cations (K, Ag), by way of non-limiting example. Alternatively, M and M' may be represented by more than one element to form a solid solution. Examples of such compounds are, but not limited to,  $\text{AgPbBi}_{0.75}\text{Sb}_{0.25}\text{Te}_3$ ,  $\text{AgPbBi}_{0.5}\text{Sb}_{0.5}\text{Te}_3$ ,  $\text{AgPbBi}_{0.75}\text{Sb}_{0.25}\text{Te}_3$ ,  $\text{AgPb}_{0.75}\text{Sn}_{0.25}\text{BiTe}_3$ ,  $\text{AgPb}_{0.5}\text{Sn}_{0.5}\text{BiTe}_3$ , and  $\text{AgPb}_{0.25}\text{Sn}_{0.75}\text{BiTe}_3$ . Additional non-limiting examples of solid solutions are given in Table 1.

It will be appreciated that although fractional numbers are used for the mole ratios, they can be combined to give the integer value for n or m. For example, in

$\text{AgPb}_{0.75}\text{Sn}_{0.25}\text{BiTe}_3$ , Pb + Sn represent M and their combined mole fractions are equal to 1, the value for m.

While the n and m values in the pure isostructural compounds provide a coarse dial to control band-gap, the solid solutions give a fine dial for band gap engineering. For example,  $\text{KPb}_2\text{BiSe}_4$  has a band gap of 0.66 eV while  $\text{KPb}_2\text{BiTe}_4$  has a band gap of less than 0.40 eV (Table 1). Therefore, solid solutions  $\text{KPb}_2\text{BiSe}_3\text{Te}$ ,  $\text{KPb}_2\text{BiSe}_2\text{Te}_2$  and  $\text{KPb}_2\text{BiSeTe}_3$  will all have band gaps that fall somewhere between 0.66 and 0.40 eV. The formation of solid solutions with these compositions provides yet another means for tuning the band gap.

The isostructural compounds of the present invention can be used in optical applications including, for example, infrared and near infrared detectors, lasers and photovoltaic cells such as solar cells by way of non-limiting example. In optical applications, at least two materials having different band gaps are layered together to give the desired optical properties. The isostructural compounds of the present invention have a wide range of band gaps that can be finely tuned to give optimal performance in such optical applications. In addition, the lattice structures are identical, allowing for superior lattice matching of the layers compared to the layering of two compounds with varying structures.

The isostructural compounds of the present invention can also be used in multi-spectral sensors. Multi-spectral sensors (e.g. long wavelength and short wavelength) offer the possibility of improved clutter rejection and improved recognition range. The proper fusing of the information from each spectral band is key to the realization of these advantages. One such application is the two color, stacked, co-located, three terminal back-to-back diodes pixel. Two color, simultaneous integration HgCdTe back-to-back diodes staring IRFPAs have been produced. Love, P. et al., Proceedings of the IRIS Detectors Specialty Group Symposium, pp.169-186 (1995). The materials of the present invention are well suited for this multispectral configuration because they provide lattice matching over a wide range of n and m. For example, a two-material stacked structure with  $\text{KPb}_2\text{BiSe}_4$  ( $E_g=0.66$  eV) and  $\text{KPb}_8\text{BiSe}_{10}$  ( $E_g=0.35$  eV) can be built either by vapor deposition techniques or by fusion bonding of two individual crystals as illustrated in Figure 3 along with the respective lattice constants, a. Current approaches using HgCdTe solid solutions (comprising HgTe and CdTe) require the growth of heterojunctions, which then requires precise lattice matching. Current techniques result in a lattice mismatch as great as 4-6%, compromising the performance of the multispectral sensor. In contrast, the isostructural compounds of the present invention can be utilized as individual compounds and therefore should not require precise compositional control at the junction. The lattice mismatch using

the isostructural compounds of the present invention is significantly less than 4-6 % and is <2% with  $\text{KPb}_2\text{BeSe}_4$  and  $\text{KPb}_8\text{BiSe}_{10}$  in a stacked structure (Figure 3).

Another application for isostructural compounds of the present invention is in thermoelectric devices. Such devices may be used for heating, cooling, temperature stabilization, power generation and temperature sensing. Recently, significant advances in the synthesis and design of new systems such as in filled skutterudites and quantum well structures provided new hope that high performance thermoelectric materials may be attainable. While the efficiency of thermoelectric coolers operating near room temperature is only about 10% of Carnot efficiency, the thermodynamics of thermoelectric cooling suggests that achieving close to 100% of Carnot efficiency is possible employing the isostructural compounds of the present invention.

Thermoelectric devices are essentially heat pumps and power generators which follow the laws of thermodynamics in the same manner as mechanical heat pumps, refrigerators, or any other apparatus used to transfer heat energy. The principal difference is that thermoelectric devices function with solid state electrical components (thermocouples) as compared to more traditional mechanical/fluid heating and cooling components. An efficient thermoelectric device is fabricated from two materials, one N-type and the other a P-type conductor. Each material is separately chosen to optimize the figure of merit,  $zT$ , where  $zT = (S^2\sigma/\kappa)T$ ;  $S$  is the thermopower or Seebeck coefficient ( $\mu\text{V/K}$ ),  $\sigma$  the electrical conductivity ( $\text{S/cm}$ ),  $\kappa$  the thermal conductivity ( $\text{W/m-K}$ ) and  $T$  the temperature ( $\text{K}$ ). Therefore, to obtain a thermoelectric material having a high thermoelectric performance, it is desirable to select a material having a large Seebeck coefficient,  $S$ , a large electrical conductivity,  $\sigma$ , and a small thermal conductivity,  $\kappa$ .

The isostructural compounds of the present invention have a high thermoelectric performance resulting from large Seebeck coefficients, large electrical conductivities and small thermal conductivities (Table 1). The Seebeck coefficients of the compounds of the present invention range from about  $\pm 30 \mu\text{V/k}$  to about  $\pm 500 \mu\text{V/k}$  and the electrical conductivities from about 10 to about 7000  $\text{S/cm}$ .

Figure 4 shows the effect of increasing temperature on the inverse of electrical conductivity (resistivity) while Figure 5 shows the effect of increasing temperature on the Seebeck coefficient of the compound  $\text{KPb}_8\text{BiTe}_{10}$ . Increasing the temperature results in a larger Seebeck coefficient.

The isostructural compounds of the present invention may be doped with selected impurities to produce P-type and N-type conductors having improved thermoelectric properties such as enhanced Seebeck coefficients and figures of merit ( $zT$ ). In an enhanced

N-type conductor, one atom is replaced by another atom having more valence electrons, wherein the extra electrons are not needed for bonding and are free to move throughout the crystal. Alternatively, a P-type conductor is formed when an atom in the isostructural compound is replaced by another atom with fewer electrons, leaving a bond vacant wherein this shortage is referred to as a hole.

The compounds of the present invention always exhibit P-type conductivity when the compounds are prepared by high temperature reaction with stoichiometric amounts of the constituent components. Enhanced P-type semiconductors can be produced from the compounds of the present invention. For the cationic sites of Bi or Sb (Group V) and Pb or Sn (Group IV), doping with one electron deficient elements such as Group IV elements (Ge, Sn, Pb) and Group III elements (Al, Ga, In, Tl), respectively, may produce more hole carriers which give rise to improved electrical properties.

The isostructural components of the present invention can be used to produce N-type semiconductor materials by doping with various impurities. Isovalent anionic dopants, where S or Se is substituted for Te and S for Se may be used in about less than 1 atomic percent. Other examples of compounds that can be used for doping are the metal halides  $SbX_3$ ,  $BiX_3$ , and  $Hg_2Cl_2$ ,  $DX_2$  where X is selected from the group consisting essentially of chlorine, bromine, iodine and mixtures thereof and D is selected from the group consisting essentially of chromium, manganese, iron, cobalt, nickel, copper, zinc, magnesium and mixtures thereof. These are examples of compounds that can be used for doping and are in no way meant to be limiting. It should be appreciated by those skilled in the art that any dopant can be used to dope the isostructural compounds of the present invention to form enhanced P-type and N-type semiconductors.

Doping of the isostructural compounds of the present invention can be achieved by introducing the desired amount of dopant during synthesis. Stoichiometric amounts of the dopant can be added to the starting materials. Alternately, the compounds of the present invention can be doped by co-melting the desired compound and the dopant and recooling the new mixture. The amount of dopant preferably ranges from 0.0001% to 4% by weight.

The isostructural compounds of the present invention may be used in a thermoelectrical conversion process in a thermoelectric conversion device. The thermoelectric conversion process using the isostructural compounds of the present invention may take any appropriate form, such as any known device and/or structure, as long as thermoelectric conversion principles are met. Such devices may be, but are not limited to, electrical power generators, heater, coolers, thermocouples, temperature sensors and radioisotope thermoelectric generators. Other thermoelectric devices that can be manufactured using the compounds of the present invention may be used in waste heat

recovery systems, automobiles, remote power generators, temperature sensors and coolers for advanced electronic components such as field effect transistors, as non-limiting examples.

- 5 The isostructural compounds of the present invention may take any number of appropriate shapes. The compounds may be used in a lump shape or they may be formed in the shape of a thin film by a growth method, vapor deposition, or other techniques known to those skilled in the art. Regardless of the shape, the isostructural compounds of the present invention have excellent conductivity and thermoelectric properties.

TABLE 1.

Compound	n	m	Lattice Parameter (Å)	Band Gap (eV)	Melting Point (°C)	$\kappa^a$ (W/m-K)	$\sigma^b$ (S/cm)	$S^c$ ( $\mu$ V/K)
AgPbBiS <sub>3</sub>	1	1	5.753	0.54	>910	1.3	25	-160
AgPbBiSe <sub>3</sub>	1	1	5.955	0.48	>920	1.0	67	-130
AgPbBiTe <sub>3</sub>	1	1	6.28	0.28	>900	1.15	300	-40
AgPbSbTe <sub>3</sub>	1	1						
AgSnBiTe <sub>3</sub>	1	1	6.1639					
AgPb <sub>2</sub> BiTe <sub>4</sub>	1	2	6.323	0.29	>850	1.2	180	-165
AgSn <sub>8</sub> BiSe <sub>10</sub>	1	8	5.926		>900	1.2		
AgPb <sub>10</sub> BiS <sub>12</sub>	1	10	6.117	0.31	>900	1.1		
AgPb <sub>10</sub> BiTe <sub>12</sub>	1	10	6.452	0.29	>850	1.1		
AgPb <sub>10</sub> SbTe <sub>12</sub>	1	10	6.441	0.29	>850	1.0		
AgPb <sub>10</sub> BiSe <sub>12</sub>	1	10	6.118					
AgSn <sub>10</sub> BiS <sub>12</sub>	1	10	6.259				6700	
AgPb <sub>10</sub> SbS <sub>12</sub>	1	10	5.905				300	
AgPb <sub>13</sub> BiTe <sub>15</sub>	1	13	6.44	0.23	>800	1.6		
AgPbBiTe <sub>2</sub> Se	1	1	6.185			1.3	400	-58
AgPbBiTe <sub>2.25</sub> Se <sub>0.75</sub>	1	1	6.19			1.1	150	-40
AgPbBiTe <sub>2.5</sub> Se <sub>0.5</sub>	1	1	6.247			1.6	77	-80
AgPbBiTe <sub>2.75</sub> Se <sub>0.25</sub>	1	1	6.274			1.15	133	-105
AgPbBi <sub>0.1</sub> Sb <sub>0.9</sub> Te <sub>3</sub>	1	1						
AgPbBi <sub>0.05</sub> Sb <sub>0.95</sub> Te <sub>3</sub>	1	1						
AgPbBi <sub>0.75</sub> Sb <sub>0.25</sub> Te <sub>3</sub>	1	1	6.261	0.268			29	-68
AgPbBi <sub>0.5</sub> Sb <sub>0.5</sub> Te <sub>3</sub>	1	1	6.261	0.27			3.91	250
AgPbBi <sub>0.25</sub> Sb <sub>0.75</sub> Te <sub>3</sub>	1	1					10	370
AgPb <sub>0.75</sub> Sn <sub>0.25</sub> BiTe <sub>3</sub>	1	1		0.18			59	-33

AgPb <sub>0.5</sub> Sn <sub>0.5</sub> BiTe <sub>3</sub>	1	1					310	
AgPb <sub>0.25</sub> Sn <sub>0.75</sub> BiTe <sub>3</sub>	1	1					685	35
AgPbBiTe <sub>1.5</sub> Se <sub>1.5</sub>	1	1	6.13					
AgPbBiTeSe <sub>2</sub>	1	1	6.078					
AgPbBiTe <sub>0.5</sub> Se <sub>2.5</sub>	1	1	6.036					
AgPbBiTe <sub>2.95</sub> Se <sub>0.05</sub>	1	1	6.223					-64
AgPbBiTe <sub>2.75</sub> Se <sub>0.25</sub>	1	1	6.245				666	-60
AgPbSb <sub>0.95</sub> Bi <sub>0.05</sub> Te <sub>3</sub>	1	1		0.37				430
KPb <sub>3</sub> BiS <sub>5</sub>	1	3	5.949	0.71	>850			
K <sub>5</sub> Pb <sub>16</sub> Bi <sub>5</sub> S <sub>26</sub>	5	16	5.947	0.69	>850			
KPb <sub>7</sub> BiS <sub>9</sub>	1	7	5.937	0.63	>850			
KPb <sub>9</sub> BiS <sub>11</sub>	1	9	5.947	0.53	>850			
K <sub>7</sub> PbBi <sub>7</sub> S <sub>15</sub>	7	1	5.975	1.02	>850			
K <sub>8</sub> PbBi <sub>8</sub> S <sub>17</sub>	8	1	6.006	1.24	>850			
K <sub>11</sub> PbBi <sub>11</sub> S <sub>23</sub>	1	1	6.009	1.30	>850			
KPbBiSe <sub>3</sub>	1	1	6.182	0.6	1004			
KPb <sub>2</sub> BiSe <sub>4</sub>	1	2	6.185	0.66	958			-515
KPb <sub>3</sub> BiSe <sub>5</sub>	1	3	6.175	0.64	977			40
KPb <sub>4</sub> BiSe <sub>6</sub>	1	4	6.154	0.56	1015			210
KPb <sub>5</sub> BiSe <sub>7</sub>	1	5	6.142	0.45	1035			500
KPb <sub>10</sub> BiSe <sub>12</sub>	1	10	6.112	0.32	>850			
K <sub>2</sub> Pb <sub>23</sub> Bi <sub>2</sub> Se <sub>27</sub>	2	23	6.111		>850			
K <sub>2</sub> PbBi <sub>2</sub> Se <sub>5</sub>	2	1	6.007	0.62	>900			
K <sub>3</sub> PbBi <sub>3</sub> Se <sub>7</sub>	3	1	6.196	0.67	>900			
KPbBiTe <sub>3</sub>	1	1		0.45	>900	<1.5		-125
KPb <sub>2</sub> BiTe <sub>4</sub>	1	2	6.469	<0.40	>900	1.7	700	-115
KPb <sub>3</sub> BiTe <sub>5</sub>	1	3	6.467	<0.38	>900	1.5	800	
KPb <sub>4</sub> BiTe <sub>6</sub>	1	4	6.479	<0.37	>900	1.7	1000	-155
KPb <sub>8</sub> BiTe <sub>10</sub>	1	8	6.458	<0.36	>900	2.1	1100	-150
KPb <sub>10</sub> BiTe <sub>12</sub>	1	10	6.472	<0.36	>900	2.2	960	-145
KPb <sub>10</sub> BiSeS <sub>11</sub>	1	10	5.9815					
KPb <sub>10</sub> BiSe <sub>3</sub> S <sub>9</sub>	1	10	6.0199					
KPb <sub>10</sub> BiSe <sub>6</sub> S <sub>6</sub>	1	10	6.0635					
KPb <sub>10</sub> BiSe <sub>9</sub> S <sub>3</sub>	1	10	6.1055					
KPb <sub>10</sub> BiSe <sub>11</sub> S	1	10	6.1336					
KPb <sub>10</sub> Bi <sub>0.75</sub> Sb <sub>0.25</sub> Te <sub>6</sub> Se <sub>6</sub>	1	10	6.3284		935		990	
KPb <sub>10</sub> Bi <sub>0.5</sub> Sb <sub>0.5</sub> Te <sub>6</sub> Se <sub>6</sub>	1	10	6.3073		935		595	
KPb <sub>10</sub> Bi <sub>0.75</sub> Sb <sub>0.25</sub> Te <sub>6</sub> Se <sub>6</sub>	1	10	6.2846		935		380	

KPb <sub>8</sub> Sn <sub>2</sub> BiTe <sub>6</sub> Se <sub>6</sub>	1	10	6.2949		860		450	
KPb <sub>6</sub> Sn <sub>4</sub> BiTe <sub>6</sub> Se <sub>6</sub>	1	10	6.27		860		40	
KPb <sub>4</sub> Sn <sub>6</sub> BiTe <sub>6</sub> Se <sub>6</sub>	1	10	6.2544		860		100	
KPb <sub>2</sub> Sn <sub>8</sub> BiTe <sub>6</sub> Se <sub>6</sub>	1	10	6.2094		860		360	
KPbSbTe <sub>3</sub>	1	1						
KPb <sub>5</sub> SbTe <sub>7</sub>	1	5	6.448				13	
KPb <sub>10</sub> SbTe <sub>7</sub>	1	5	6.459				215	
KSnBiTe <sub>3</sub>	1	1					150	
KSn <sub>5</sub> BiTe <sub>7</sub>	1	5					230	
KSn <sub>10</sub> BiTe <sub>12</sub>	1	10	6.292				990	
KSnSbTe <sub>3</sub>	1	1					210	
KSn <sub>5</sub> SbTe <sub>7</sub>	1	5	6.278				2630	
KSn <sub>10</sub> SbTe <sub>12</sub>	1	10	6.363				4250	

- <sup>a</sup> Thermal conductivity
- <sup>b</sup> Electrical conductivity at room temperature.
- <sup>c</sup> Seebeck Coefficient at room temperature.

Although the present invention has been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and the scope to the invention.



We Claim:

1. A con

A is at le

7. A conductive material having the general formula  $A_n M_m M'_n Q_{2n+m}$  wherein:

A is at least one element selected from the group consisting of Li, Na, K, Rb, Cs, Tl,  
;

M is at least one element selected from the group consisting of Pb, Sn, Ge, Ca, Sr,

5 Ba and any divalent transition metal;

M' is at least one element selected from the group consisting of Bi and Sb; and

Q is at least one element selected from the group consisting of Se, Te and S.

2. The conductive material of Claim 1 wherein n and m are integers.

3. The conductive material of Claim 1 wherein the material possesses an NaCl-cubic lattice structure.

4. The conductive material of Claim 1 wherein A is K, M is Pb and M' is Bi.

5. The conductive material of Claim 1 wherein A is Ag, M is Pb and M' is Bi.

6. The conductive material of Claim 1 wherein A is K, M is Sn and M' is Bi.

7. A semiconductor device comprising the conductive material of Claim 1.

8. An infrared detector comprising the conductive material of Claim 1.

9. A photovoltaic element comprising the conductive material of Claim 1.

10. A multispectral sensor comprising the conductive material of Claim 1.

11. A thermoelectric device comprising the conductive material of Claim 1.

12. A solid solution comprising a conductive material having the general formula  $A_n M_m M'_n Q_{2n+m}$  wherein:

A is at least one element selected from the group consisting of Li, Na, K, Rb, Cs, Tl, and Ag;

5 M is at least one element selected from the group consisting of Pb, Sn, Ge, Ca, Sr, Ba and any divalent transition metal;

M' is at least one element selected from the group consisting of Bi and Sb; and

Q is at least one element selected from the group consisting of Se, Te and S.

13. The solid solution of Claim 12 wherein A is at least two elements selected from the group consisting of Li, Na, Rb, Cs, Tl and Ag.

14. The solid solution of Claim 12 wherein Q is at least two elements selected from the group consisting of Se, Te and S.

15. The solid solution of Claim 12 wherein M' is Bi and Sb.

16. The solid solution of Claim 12 wherein M is at least two elements selected from the group consisting of Pb, Sn, Ge, Ca, Sr, Ba and any divalent transition metal.

17. The solid solution of Claim 12 wherein the solid solution possesses a NaCl-like cubic lattice crystal structure.

18. A semiconductor device comprising the solid solution of Claim 12.

19. An infrared detector comprising the solid solution of Claim 12.

20. A photovoltaic element comprising the solid solution of Claim 12.

21. A thermoelectric device comprising the solid solution of Claim 12.

22. A P-type conductive material comprising:

(a) a conductive material having the general formula  $A_nM_mM'_nQ_{2n+m}$  wherein:

A is at least one element selected from the group consisting of Li, Na, K, Rb,

Cs, Tl, and Ag;

M is at least one element selected from the group consisting of Pb, Sn, Ge,

Ca, Sr, Ba and any divalent transition metal;

M' is at least one element selected from the group consisting of Bi and Sb;

and

Q is at least one element selected from the group consisting of Se, Te and S;

(b) a dopant.

23. The P-type conductive material of Claim 22, wherein the dopant is selected from the group consisting of Ge, Sn, Pb, Al, Ga, In, Ti and mixtures thereof.

24. An N-type conductive material comprising:

(a) a conductive material having the general formula  $A_nM_mM'_nQ_{2n+m}$  wherein:

A is at least one element selected from the group consisting of Li, Na, K, Rb,

Cs, Tl, and Ag;

M is at least one element selected from the group consisting of Pb, Sn, Ge,

Ca, Sr, Ba and any divalent transition metal;

M' is at least one element selected from the group consisting of Bi and Sb;

and

Q is at least one element selected from the group consisting of Se, Te and S;

and

(b) a dopant.

25. The N-type conductive material of Claim 24 wherein the dopant is a  $\text{SbX}_3$ , wherein X is a halide.

26. The N-type conductive material of Claim 24 wherein the dopant is  $\text{BiX}_3$ , wherein X is a halide.

27. The N-type conductive material of Claim 24 wherein the dopant is  $\text{Hg}_2\text{Cl}_2$ .

28. The N-type conductive material of Claim 24 wherein the dopant is  $\text{DX}_2$  where:  
D is at least one element selected from the group consisting of Cr, Mn, Fe, Co, Ni, Cu, Zn and Mg; and  
X is at least one element selected from the group consisting of Cl, Br and I.

29. The N-type conductive material of Claim 24 wherein the amount of dopant is from 0.0001% to 4% by weight.

30. A thermoelectric device comprising the N-type conductive material of Claim 24.

31. A semiconductor device comprising the N-type conductive material of Claim 24.

### ABSTRACT

A family of isostructural compounds have been prepared having the general formula  $A_nPb_mBi_nQ_{2n+m}$ . These compounds possess a NaCl lattice type structure as well as low thermal conductivity and controlled electrical conductivity. Furthermore, the electrical properties can be controlled by varying the values for n and m. These isostructural compounds can be used for semiconductor applications such as detectors, lasers and photovoltaic cells. These compounds also have enhanced thermoelectric properties making them excellent semiconductor materials for fabrication of thermoelectric devices.

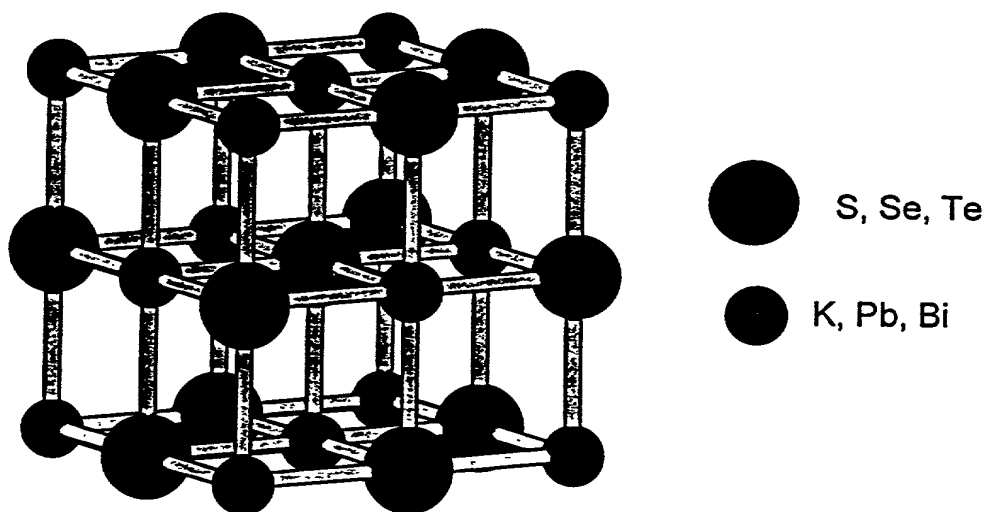
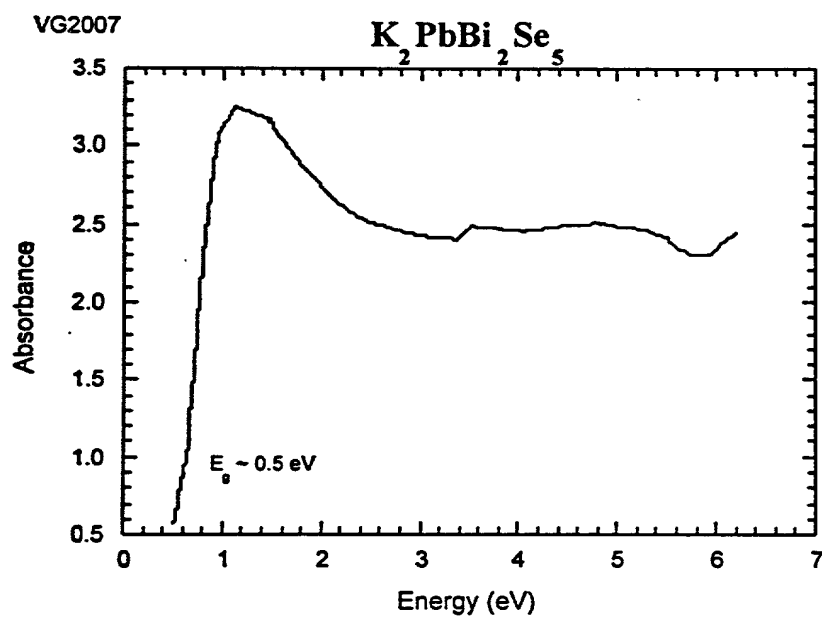
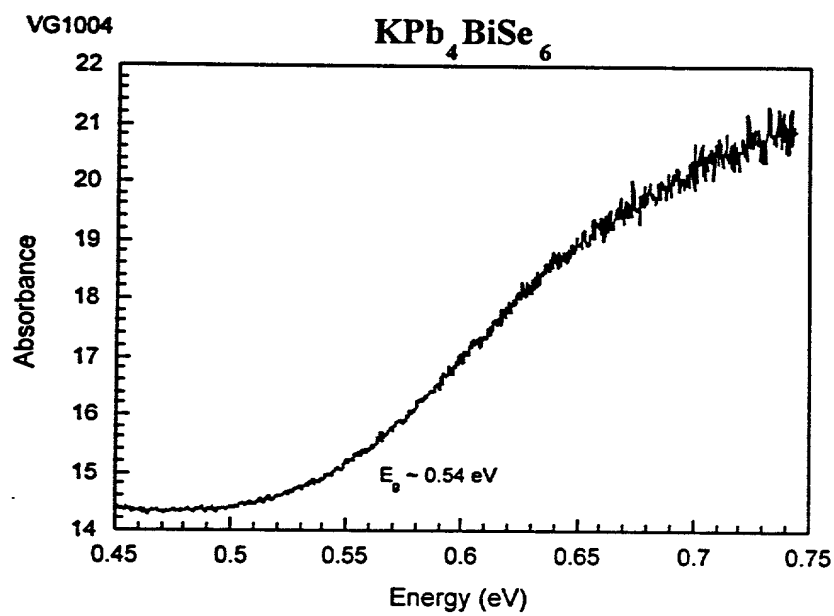


FIGURE 1

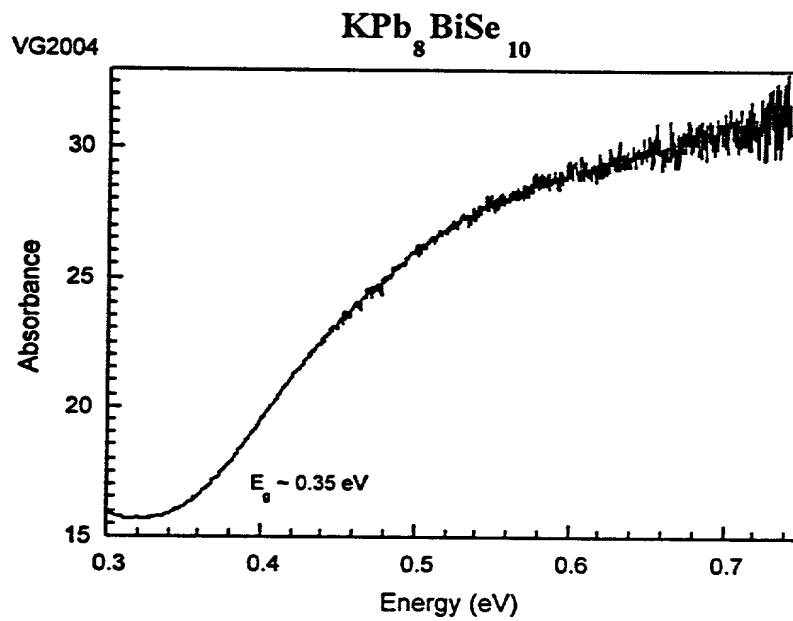


**FIGURE 2A**



**FIGURE 2B**





**FIGURE 2C**

PbSe

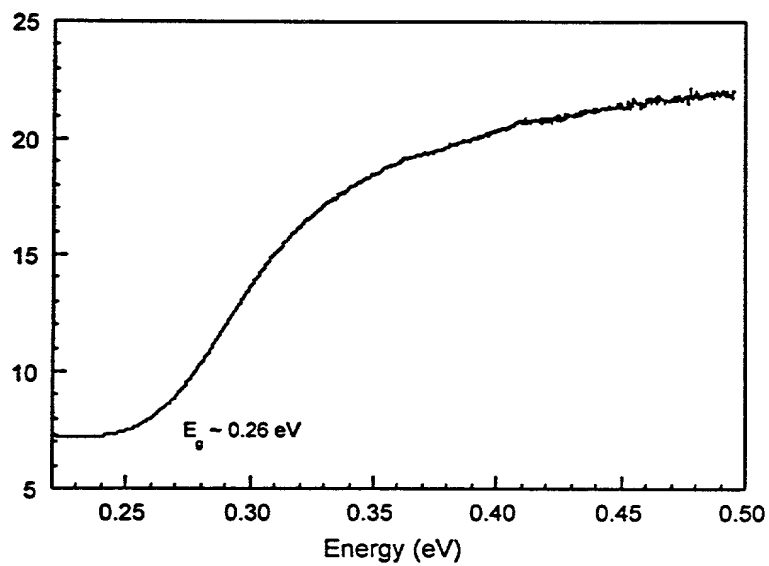


FIGURE 2D

$\text{KPb}_2\text{BiSe}_4$   
long wavelength IR

$E_g = 0.66 \text{ eV}$   
 $a = 6.185 \text{ \AA}$

$\text{KPb}_8\text{BiSe}_{10}$   
short wavelength IR

$E_g = 0.35 \text{ eV}$   
 $a = 6.107 \text{ \AA}$

cubic substrate ( $\text{BaF}_2$ )

lattice mismatch  $< 2\%$

**FIGURE 3**

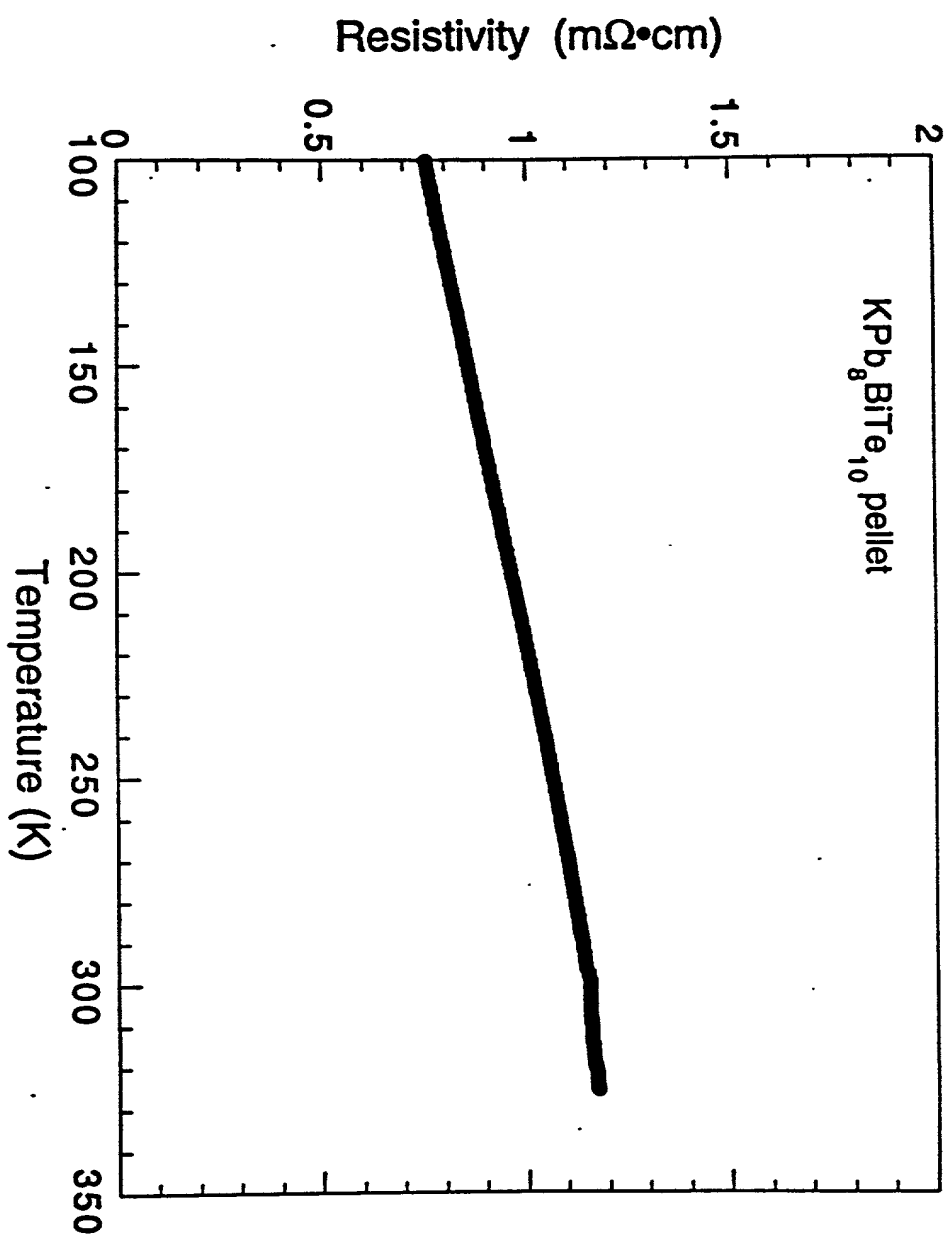


FIGURE 4

